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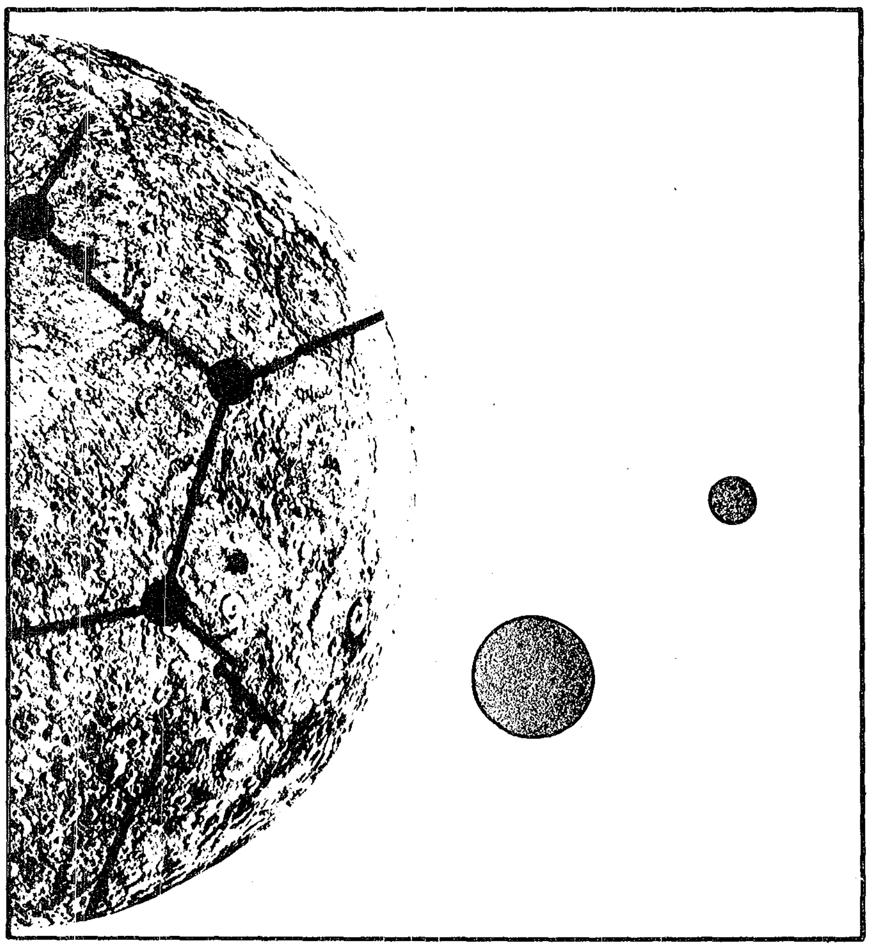
CONCEPT FOR A RESEARCH PROJECT IN
EARLY CRUSTAL GENESIS



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CONCEPT FOR A RESEARCH PROJECT IN

EARLY CRUSTAL GENESIS

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Preface

This paper is intended to be an interim document to serve the Early Crustal Genesis (ECG) Project until early 1982, when a detailed research plan will be released. The present discussion has grown out of the deliberations of three meetings (January, March and May of 1981) of an *ad-hoc* steering committee charged with the task of developing a project philosophy.

One of the key recommendations of this group led to the formation of eight discipline-oriented working groups. These groups will meet simultaneously at Airlie House, Virginia, November 13–17, 1981, to formulate the long-range research plans of the ECG effort. The present document will provide background information to the participants in the November meeting. It is also intended to be a vehicle to communicate the ECG project concepts to a variety of governmental agencies in the United States and elsewhere, as well as to other relevant national and international scientific organizations.

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Introduction

Over the past several decades vast amounts of new data have been acquired relevant to the origin and evolution of the planets. As a result, a revolution has occurred in our approach to the evolution of crust-mantle systems of planetary bodies, with the appreciation that all but the smallest bodies in the solar system probably underwent a period of extensive melting and differentiation during their first few hundred million years of existence.

The Earth, for at least the next decade, will be the only planetary body for which extensive new data sets can be obtained to rigorously test models of planetary evolution. Knowledge gained from the Earth will advance our understanding of planetary evolution and can be used: (1) to narrow the range of planetary models that must be tested, (2) to determine the critical data sets that will test the validity of the models, and (3) to define better the priorities of exploration of planetary bodies. Only a limited understanding of early Earth history exists, especially of the formation and early evolution of its crust, a major planetary-scale problem. Inasmuch as the most critical data for planetary models are incorporated in the oldest parts of the Precambrian shields of the Earth's continents, their study is extremely important to the general application of planetary models for crust-mantle evolution.

Through combined geological, geochemical, petrological, and geophysical studies of data from the Moon, there have been significant advances made in development of models for the Moon's thermal history, crustal formation, mantle evolution, volcanic activity, tectonic sequences, early meteoritic bombardment effects, and many other processes. The models, in order to be more generally applied and to be understood in the broader planetary context, must be further tested, modified, and verified by applying them to other planetary bodies of different size, composition, and location. For example, most of the "pristine" lunar highland rocks appear to be subsequently-altered magmatic cumulates. However, the once-accepted hypothesis that these cumulates were derived from a global magma ocean several hundred kilometers deep is in disrepute, and either an alternative hypothesis or magma ocean petrogenesis needs to be closely examined.

Our understanding of crustal genesis and evolution outside of the Earth-Moon system is very incomplete, but we have enough data to ask, and possibly answer, some significant questions. For example, most of the Venus topography lies near a single elevation, which likely represents a fundamental crustal layer of the planet. Is this layer a primordial feature, as understood for the lunar highlands crust; is it a result of secondary differentiation processes associated with lithospheric recycling; or did it form from some process totally unfamiliar to us? There is also intense interest in deciphering the present tectonic style for Venus. There is speculation that the venusian lithosphere is too buoyant to subduct and is a possible analogy to the terrestrial Archean lithosphere.

In all, taking these other planets into context with studies that view the Earth's crustal genesis and evolution on a global scale should lead to a better understanding of crustal genesis processes in general and differences in crustal genesis among the terrestrial planets in particular. The Early Crustal Genesis (ECG) Project is an effort that applies the concept of a multi-disciplinary, multi-institutional approach to the questions of genesis and early evolution of the crusts of the terrestrial planets, and in particular strives for a multi-planet synergism. ECG will strive toward a level of synthesis and cross-disciplinary research among the terrestrial Archean and planetary communities that will not otherwise come into being.

The initiation of a research project on Early Crustal Genesis, designed to stimulate research and cross-disciplinary interaction and synthesis in the planetary and terrestrial Archean communities, seems appropriate at this time. On the planetary side, the Lunar Highlands Initiative is active, vigorous, and in the process of expanding its focus from the early lunar crust toward moon-Earth and moon-meteorite

comparisons. The terrestrial Archean community is very large, active, and includes an extremely broad and diverse range of research interests. The same is true on a smaller scale for meteorite research, some of which is highly relevant to bulk chemical composition and to the early differentiation history of terrestrial planets. Although a normal level of scientific cross-interactions exists among these groups, it is unlikely that any adequately broad interdisciplinary, organized effort to define the current state of knowledge of the origin and evolution of early planetary crusts in general, to initiate or encourage particular research directions, and to attempt to synthesize new results in the context of the general problem will emerge spontaneously from any of these communities, or from the various panels, commissions and study groups currently operating under the sponsorship of international societies.

Reasonable criteria for launching a research project might be:

(a) Scientific importance and range of the topic

(b) Chance for "success" (i.e., a positive contribution to both the individual research areas and to interaction and synthesis among them)

(c) "Maturity" of the individual research areas (e.g., sufficient data base and numbers of active workers in most of the primary areas to ensure that the products of the study are not largely lists of fundamental unknowns requiring many years of further work to illuminate) and

(d) Scientific breadth of the topic assessed in terms of involvement of specialists in different communities that have not tended to interact extensively so that the project rationale is fulfilled by bringing representatives of such communities together for interaction and overview in workshops, conferences and in generating written products.

Judged on these criteria, initiating the ECG research Project seems appropriate at this time.

Goals, Objectives, and Strategy

The overall *goal* of the Early Crustal Genesis Project is to develop and refine a set of testable models for formation and evolution of the crusts of the terrestrial planets, highlighting both their similarities and differences. This represents a major new research effort, involving acquisition of new data sets as well as synthesis of already existing planetary data and theory. The specific *objectives* are to identify the key physical and chemical processes and the initial conditions for evolutionary models, to understand the evolution of planetary crusts in relationship to the overall history of individual planetary bodies, and to understand the reasons for the differences in evolution among the various planetary crusts. The *strategy* is to adopt an interdisciplinary approach and cross-planetary approach to the question of crustal genesis. Specifically, this program will strive:

(a) To foster cooperative research among scientists and organizations studying the Archean and those studying the crusts of other planets. Many national and international research efforts are underway on various aspects of the Earth's crust and other planetary crusts. Communication and collaboration between these efforts should provide a synergistic relationship.

(b) To foster a significant understanding of the evolution of rocky planets, especially the generation of crust. Recent studies have led to new hypotheses about the melting, differentiation, and energy sources involved in crust-mantle systems. Modeling and testing of hypotheses for the formation and evolution of planetary crusts should receive substantial effort.

(c) To foster the utilization of global data sets, including those collected from Earth orbit, in studying the planets. These data can provide new insights into global-scale processes and patterns.

(d) To identify the physical processes and initial physical and chemical conditions which determine the paths of crustal formation and evolution on the terrestrial planets: parameters such as size, initial composition, and volatile content should cause significant variations in these paths. The extent to which these and other parameters may determine such paths should be identified.

(e) To encourage examination of the Earth's Archean crust from a global perspective as an example of the evolution of a rocky planet. The early crust of the Earth contains petrologic, chemical, isotopic, structural, tectonic, and geophysical data that can be used to test complex models of crustal evolution. The accessibility of new sources of data allows for a continuously iterative process in revisions of models and selection of data, thus making the Archean crust an excellent example for such studies.

A key and crucial concept in the ECG Project is that funds become available to carry out the research outlined in the research plan. In the United States it is envisaged that NASA and NSF will be the key funding agencies. It is recognized that each of these agencies approaches research funding in a different manner and those scientists seeking research support must accommodate this fact. Additionally, it is imperative to develop an inter-agency agreement that as a minimum: (1) defines the purviews for funding and (2) defines the purviews for meeting and publication sponsorship. Foreign investigators will seek funding from their own national agencies or other organizational entities, as appropriate.

Precursor Activities

Certain cross-disciplinary elements exist that may be viewed as both precursor to and continuing activities of an ECG Project.

Lunar Highlands Initiative

The ancient lunar crust has been the subject of intensive study for about the past three years as a focused research effort organized by LAPST (Lunar and Planetary Sample Team) under the title of "Lunar Highlands Initiative." A Lunar and Planetary Institute (LPI) topical conference on The Lunar Highlands Crust in November, 1979, and the conference proceedings (Papike and Merrill, 1980), as well as the Apollo 16 workshop held in November, 1980, and its subsequent report (James and Hörz, 1981), are the major interim reports of research carried out by this group. Subject areas covered include regional characteristics, petrology, chemistry and chronology of the highlands. A second workshop on "Magmatic Processes in the Generation of Primordial Planetary Crusts: Magma Oceans and Stratiform Layered Intrusions" was held in August, 1981, in the Stillwater Complex, Montana. A workshop on "Lunar Breccias and Meteoritic Analogs" will be held in November, 1981, at LPI. Workshop reports from these last two meetings will be available in the fall of 1981, and the winter of 1982, respectively.

Workshops on Early Evolution of Planetary Crusts

In February of 1979 a workshop was held at LPI on "Ancient Crusts of the Terrestrial Planets" (Papike *et al.*, 1979). This workshop encouraged interaction between scientists studying the early crusts of the planets of the inner solar system. The workshop report was distributed in August, 1979.

A second workshop, "Early Crustal Genesis: Implications from Earth," was held in November, 1980 (Phinney, 1981). This workshop was a direct forerunner of the 1981 ECG activities; it explored ways in which studies of the Earth can contribute to a more general understanding of the origin and early evolution of planetary crusts.

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Present Project Organization and the Airlie House Meeting

Any attempt to structure the organization of ECG leads to natural definitions of key themes or problem areas. There are any number of ways to define an inclusive set of such entities and the *ad-hoc* steering committee settled on eight such areas of inquiry which in turn define eight working groups:

I Planetary Volatiles
II Physical and Chemical Evolution
III Surface Processes
IV Planetary Formation
V Metallogenesis
VI Crustal Features and Their Development
VII Tectonics
VIII Paleobiology

A similar set of themes or problem areas was presented by Phinney (1981, Appendix A) and serve to illustrate a second approach to an organizational structure of ECG in that this latter approach is composed in part of one-to-one correlations with some of the eight working group subjects above, and in part of various linear combinations of these subjects. This underscores the point that the present eight working groups are merely a consistent but non-unique set and serve to define an interim structure for the purpose of organizing the Airlie House project meeting in November.

During the first two days of the meeting, the presently-defined working groups will meet individually, outlining and reviewing basic research issues within the individual subject areas. The last two and one-half days will be devoted to inter-group and plenary activities, the exact nature of which will be determined in response to issues raised in the first two days. It is envisaged that some working groups will remain intact, some may combine, and new groups may be defined that cluster about specific problem areas. The dynamic nature of these activities will be ensured by frequent convening of the steering committee during the course of the meeting. The steering committee, as presently organized, consists of working group conveners plus four additional members, individually concerned with Earth, Moon, meteorites, and the other terrestrial planets. *One goal of the Airlie House meeting is to create a permanent organizational structure for ECG. It is anticipated that in a number of problem areas, the Airlie House meeting will serve to nucleate working groups that are in fact research consortia.* The various organizational entities that emerge from the meeting will maintain a high degree of autonomy. It will be the responsibility of the steering committee to ensure that: (1) appropriate levels of communication between groups exist, (2) the project remains focused on its goals, and (3) an increasing degree of interdisciplinary and cross-planetary activity develops as the project matures.

A key result of the Airlie House meeting will be the research plan; it will include both the scientific and organizational information that is necessary to develop the program. The scientific information will include: the current status of research (including major questions), what research is needed to produce significant advances, and what accomplishments can realistically be expected over the next ten years. Organizational information will include suggestions for the best combination of approaches to the research (field workshops, consortium projects, individual research proposals, large cooperative research proposals, etc.), modes of communication (small topical conferences, large conferences, special sessions at national or international meetings, types of publications), sources of funding in various countries and organizations, and nature of coordination between various government agencies, panels, commissions, etc.

The results of ECG-related research will be published primarily in the refereed journals, although volumes of extended abstracts and special issues of journals with collected papers are anticipated. Yearly

compilations will be made of all written products related to ECG. A synthesis volume, authored by a small number of scientists, highlighting the results of the research and future directions, will emerge near the end of the project.

One of the issues to be raised at the Airlie House meeting will be to determine to what extent the project will strive toward collection and curation of representative sample suites of Archean rocks that may be subsequently studied by individuals and research consortia, as is done for the lunar samples and Antarctic meteorites.

Synopsis of Working Group Themes

Below is a brief summary of the working group themes. Detailed discussions are found in Appendix A.

I Planetary Volatiles

The volatile elements are a controlling factor in many of the details of planetary development. Initial distribution, abundance, and chemical composition of the volatile inventory may determine the major evolutionary tracts taken by a primitive planetary assemblage as it internally differentiates to form a core, mantle and crust. The types, time scales, and ultimate extents of petrologic and tectonic processes in early stage differentiation are sensitive to the influence of H_2O and CO_2 in determining equilibrium mineral associations, chemical partitioning, and rates of dynamic processing. Some volatiles, particularly H_2O, may strongly effect the creep strength of rocks, with profound consequences for the rates of convection and heat transport. Volatiles influence the solidus as well, enhancing melting, or by their absence, inhibiting melting, and therefore affect heat transport in melt phases. The mass and composition of a planetary atmosphere (and the hydrosphere, biosphere, and the sedimentary columns, if they exist) may provide a first order lower limitation on primordial volatile inventory, but say little about how volatiles were initially distributed within the planet, or when, how, to what extent, and with what chemical composition the gases were transported from the interior, or were returned to the interior by entrainment in subducted slabs during the geologic history of the planet. On the Earth, samples of paleoatmosphere may have been trapped and preserved in old sedimentary rocks. If so, they will provide direct clues to terrestrial outgassing chronology and perhaps to ancient atmosphere states. Origin and development of the earliest biosphere is sensitively related to the chemical composition and evolution of its ambient, atmospheric environment.

II Physical and Chemical Evolution

The nature and effectiveness of how a recently condensed planet redistributes heat, mass, accretional energy and chemical species have a strong effect on the physical and chemical evolution of that planet. Among the obviously important mechanisms are diffusion, large-scale advection (i.e., mantle convection), magmatic transport and migration of volatiles. Planetary evolution, be it thermal or chemical, is affected by each of these mechanisms and what differs with specific application is simply the relative importance of the various processes. Accordingly the essential wholeness of the subject of transport mechanisms will emerge only once the various constituencies that treat different evolutionary problems, including those dealing with high-precision isotopic analyses, high-pressure experimentation, and petrogenetic and thermal modeling, begin to integrate their special knowledge. ECG will provide a conscious effort to stimulate the interaction between these different constituencies.

III Surface Processes

Planetary surfaces reflect a variety of processes, including internally generated tectonism and volcanism, external phenomena such as impact, and interactions between crustal materials and volatiles in atmospheres and hydrospheres. Thus by nature, the study of surface processes is highly interdisciplinary and interactive, involving input ranging from synoptic planetary imagery to detailed geochemical and isotopic studies of the earliest supracrustal rocks of the Earth. With few exceptions, the planetary and terrestrial Archean data bases have traditionally remained separate. Although the details of a specific process may be unique to a particular planetary body, ECG will provide a focus for the integration of principles and interplanetary trends. For example, terrestrial data, available from detailed geomorphic, geochemical and petrologic studies, will provide needed direct and indirect constraints on the physical and chemical interaction of crustal materials with planetary volatiles as well as atmospheric evolution. Such constraints are necessary for analog studies and evolutionary models for processes operating on bodies such as Mars and

Venus. Conversely, evidence of an early period of intense impact cratering and widespread planetary volcanism is available from planets such as the Moon and Mercury, which have preserved portions of their earliest crusts, and are primary parameters in evolutionary models of Earth where evidence of the earliest crust is lacking.

IV Planetary Formation

The formation of the terrestrial planets is a rather ill-constrained problem because, on the one hand, direct evidence is scant, while on the other, it was a secondary process to the formation of the sun and major planets. However, consideration of formation is necessary to any rational discussion of early crustal genesis because differences among the terrestrial planets are dependent on formation conditions; by far the greatest energy inputs to planetary evolution occurred in this period, and isotopic data require differentiation of the lunar and meteorite parent body crusts too early to be driven by alternative energy sources.

The investigation of planetary formation is a multi-disciplinary exercise, entailing study of orbital dynamics, impact physics, meteorite chemistry, planetary thermal modeling, and other problem areas. Much of the progress toward eventual solution of these problems is necessarily being made on idealizations and analogies, such as cratering events, isotope evolution models, planetary rings, etc.

V Metallogenesis

Ore deposits abound in the ancient rocks of the Earth. Much of the exploitable deposits of base metals (e.g., Cr, Ni, Cu, Fe, Mn) and platinum group elements (e.g., Au, Ag, Pt, Pd, Rh, Ir) come from Archean rock associations. For practical reasons, considerable effort has been devoted toward understanding the modes of occurrence and origins of these mineral deposits. Although we know that the record of mineralization can be correlated with changes in Earth's structure and behavior, much more can be learned from these deposits about broad-scale planetary processes which affected Earth's early mantle, crust, hydrosphere, and atmosphere. Studies of those deposits which owe their origins to magmatic processes will yield direct constraints on the evolution of the early crust-mantle system. Questions regarding the nature of and interactions between the early oceans, atmosphere, and crust can be addressed by studies of Archean chemical and clastic sedimentary ore deposits. Metallogenic processes can also yield constraints on the nature of the largest-scaled planetary processes such as core formation and late additions of meteoritic elements due to impacts. The results of the proposed project, together with detailed models of the construction and evolution of planets, may allow the prediction of likely sites of new mineral deposits on Earth and the assessment of potential deposits on the other planets.

VI Crustal Features and Their Development

Observed features of the crust and their sequence of development form a basic data set that constrains models of crustal evolution. To better understand crustal evolution, several features require more detailed study.

For the Earth's crust (especially early Precambrian) there are at least four considerations: (1)secular trends in volumes and compositions of rocks including specific trends in greenstone belts and high grade terranes, general features such as associations of rock trends with tectonic trends, and extent of recycling of crustal materials; (2) structures and their tectonic significance including recognition of horizontal versus vertical processes, distribution of shallow versus deep patterns, and displacements between crustal blocks; (3) growth of continental crust including the question of continuous, spasmodic or one major growth, diachronous differences in growth patterns, and relative roles of magmatic versus tectonic processes; (4) features related to tectonic problems such as the basement on which greenstones were deposited, the initial extent of greenstone terranes, and the nature of Archean sedimentary basins.

For the lunar crust there are several aspects: the nature of any pristine rocks from primordial differentiation or the postulated magma ocean, the meaning of many crustal igneous rock ages at about 4.2 b.y., the origin of KREEP rocks, the relation of secular rock trends and thermal evolution, and the meaning of gravity-topographic relations. For the crusts of other planetary bodies there are such problems as the nature of tectonic patterns and their relation with crustal composition and the interpretation of meteorites as crustal materials from other planetary bodies such as asteroids.

Study of these features should allow comparison of various planetary bodies to emphasize the similarities and differences in their characteristics and sequences of development and, thereby, provide constraints on models.

VII Tectonics

Tectonics, the large-scale evolution of planetary lithospheres, is intimately related to planetary thermal history; it is the response of the rigid outer shell of a planet to the expelling of its internal heat. In that sense, the study of both present and past tectonic events and thermal evolution provides sets of mutual constraints. The style of tectonic deformation appears to be fundamentally different on each of the terrestrial planets and thus collectively the planets provide a mutual set of variable parameters to test tectonic models in space and time. The trend of crustal evolution on the Moon and Mercury, to Mars, and to Venus displays an increasing complexity in tectonic style and, as such, presents a "series of experiments" in planetary evolution, particularly the early phases. The most general aspect to be considered in ECG concerns the development of a model to predict the tectonic outcome given the thermal evolution of a planet. The interaction of those concerned with tectonic evolution of the terrestrial planets with those specifically studying the Earth's Archean provides a vehicle for model development which, for example, depends on: (1) understanding the tectonic regime on the Earth from Archean through Phanerozoic, (2) contrasting this with the tectonic style of Venus, which presumably has roughly the same thermal potential as the Earth, and (3) contrasting these large terrestrial planets with the smaller ones, which presumably now display the style of tectonics seenon planets in the last stages of their thermal evolution.

VIII Paleobiology

The course of early biologic evolution can be inferred from microfossils and other biological traces preserved in sedimentary rocks, chemical and isotopic changes attributable to organisms, analysis of the evolutionary relationships of modern microbes, and theoretical examination of hypothetical early ecosystems. No single line of evidence is compelling by itself; our knowledge depends on the combination and reconciliation of a diversity of tenuous clues derived from geology, paleontology, geochemistry, microbiology, biochemistry, and geophysics. New syntheses are emerging, stimulated by more and better data on Archean geology and paleontology, improved experimental techniques in molecular biology, and more quantitative knowledge of biochemical interactions. The goal is to deduce how, when, and why the metabolic capabilities of primitive microbes evolved, and how evolving life impacted the chemical and physical properties of Earth's atmosphere, ocean, and crust.

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Appendix A

Detailed Discussion of Working Group Themes

The following eight discussions present a detailed introduction to research themes and broadly define the scopes of interest of the eight working groups. These essays are necessarily preliminary and are meant to be the starting point for the more extensive discussions to take place at the Airlie House meeting in November, 1981.

As would be expected, there are various levels of overlap among the eight topics. All eight working groups have the same goal, of course: understanding the genesis and early evolution of the crusts of the terrestrial planets. Each individually brings a different emphasis or focus to bear.

I Planetary Volatiles

Introduction

The goal is to deduce the inventories of volatiles through time in planetary interiors and atmospheres, and their role in the petrology, geochemistry and geophysics of differentiation and material transport. The primary focus will be on Earth, and on Mars and Venus for comparative studies. Meteorite data are essential: they provide the best first-order estimates of the probable initial complement of volatile elements and compounds in the primary preplanetary matter from which the terrestrial planets accreted.

Problems

(1) Initial Inventories of Volatiles in Protoplanetary and Accreted Planetary Matter

What was the "time zero" distribution of volatiles within the accreted planet: was there a significant component of deep-seated volatiles, or were they added primarily in a late-stage surficial accretion of gas-rich matter? Consequently, did the petrologic and tectonic processes of early-stage differentiation proceed in a "dry" or "wet" environment? How would these differences affect equilibrium mineral assemblages, chemical partitioning, and rates of dynamic processes?

(2) Accretional Time-scales

Can the excess radiogenic/fissiogenic Xe isotopes known to be present in the atmospheres of Earth and Mars be related to bulk planetary inventories of ^{129}I, ^{244}Pu, ^{129}Xe, ^{136}Xe, and to the I-Xe and Pu-Xe systematics of meteorites in such a way that a "formation interval" for a terrestrial planet, relative to the time(s) of accretion, differentiation, and cooling of meteorite parent bodies, can be calculated with some confidence? Current estimates for the formation interval of the Earth range from 0 to about 100 m.y. later than the meteorites. These calculations, however, assume *no* radiogenic ^{129}Xe in the protoplanetary source matter. This in turn implies either rather special temperature conditions in the nebula during this interval (hot for a long time, so that radiogenic ^{129}Xe is lost as it is generated) and small accreting bodies (so that gases can be effectively lost), or specific types of proto-Earth volatile carriers such as CI or CM meteoritic matter with high Xe/I ratios.

(3) Extent and Importance of Mantle and Other Possible Volatile Reservoirs Through Time

What were the initial inventories for each chemical species, and how did transport processes and other source/sink mechanisms alter these inventories through geologic time? What is the elemental mass balance of transported volatiles? Is it identical to the mass balance in local "source" regions, for example where volatiles exist in equilibrium with melt before removal?

(4) Experimental Petrology of Reactions in Rock Systems with Volatile Components

What are the consequences of phase and geochemical equilibria with and without H_2O, CO_2, etc. for the composition and physical properties of planetary mantles and crusts?

(5) Isotopic Evidence and Constraints on Source Regions

Interpretations of Sm-Nd and Rb-Sr isotopic data indicate that separate isotopic reservoirs exist in the Earth; one is near-chondritic in isotopic composition. Does this reservoir also contain the source of the ^{3}He flux to the surface at present, or the excess ^{129}Xe in a Harding Co. CO_2 well and possibly in scattered ultramafic xenoliths from Hawaiian basalts? The source region of mid-ocean ridge basalts appears highly depleted, yet the ridges are a source of ^{3}He and heat. How are volatiles transported from a reservoir to the

surface; is it possibly through an intermediate reservoir? Present models of isotopic reservoirs in the Earth are very rudimentary, and there are few constraints on their possible locations.

(6) Thermal Evolution and Volatile Transport Within Planets

The transport of heat from interior to surface by advection and diffusion must be paralleled in some ways by volatile transport. Diffusion rates in solids are very low, but transport along grain boundaries may be much more rapid, especially for small atoms like He or chemically active molcules such as H_2O. At present little data exist, and it is difficult to constrain the magnitudes of effective diffusion rates for most volatiles. Transport can also occur by bulk movement of fluids—this obviously dominates near the surface where volcanism and direct venting occur. But how are volatiles transported to near-surface environments? The pattern of convective flow determines large-scale advection of volatiles—but does heat diffuse to the surface more or less rapidly than volatiles once it is near? The postulated heat flux from the core is presumably ultimately transported to the surface. Are deep-seated, possible primordial volatiles similarly transported? Perhaps diapirs and "plumes" transport both. The presence of some volatiles (mainly H_2O) strongly affects the creep strength of rocks resulting in more rapid convection and heat transport. Volatiles can depress the solidus as well, enhancing melting and heat (and volatile) transport in a melt phase. Does this provide a feedback mechanism causing thermally active planets to lose most of their volatiles by melting and convection before stiffening up?

(7) Transport Mechanisms and Fluxes through Planetary Surfaces

Volcanism and direct venting are the most obvious modes of outgassing. But are volatiles also transported by diffusive processes through solid planetary crusts? (Oceanic heat flow provides a good analogy—heat is convected vertically at ridges, and is subsequently lost by diffusion as the lithosphere cools.) Early in a planet's history, vigorous convection and meteorite bombardment may efficiently expose material at the surface where it can lose volatiles. The formation of a solid crust may later inhibit this rapid loss. The introduction of volatiles into the base of the crust by diffusion or deep-seated volcanism may be one of the primary modes of mantle outgassing.

(8) The Reverse Surface Flux: Trapping, Storage and/or Recycling of Volatiles; Geochemical Cycles

What is the flux and chemical/molecular/isotopic composition of atmospheric and rock-weathering volatiles returning to the solid earth by trapping in sediments, subduction of oceanic sediments, chemical reactions with surface rocks, etc.? What was it in the past? There are also losses from the atmospheric inventory in the other direction—exospheric flux of the lightest species to space. Relative abundances of atmospheric noble gases differ from the so-called "planetary pattern" in meteorites in being underabundant in Xe by roughly an order of magnitude. Is this evidence for non-chondritic relative abundances in proto-Earth matter, or has it resulted from preferential Xe absorption on sediments? Early studies of gases in shales and cherts indicated that the extant sedimentary column, plus subducted sediments, were sufficiently Xe-rich to explain the atmospheric depletion, but recent analyses cast considerable doubt on this. Xe also appears to be deficient in the martian atmosphere by a similar factor. Is it trapped in the regolith, or is this another clue that elemental ratios of protoplanetary noble gases were different from the meteoritic "planetary" pattern?

(9) Composition and Chemical Evolution of Planetary Atmospheres

What was the composition of the primordial terrestrial atmosphere? What was the initial redox state, how did it evolve and what is its connection with paleobiological studies of Earth's earliest biosphere? What is the relation of atmospheric chemical composition to prebiotic syntheses, to the origin of life, and to evolution

of biologic energy conversion from fermentation to anoxygenic photosynthesis to aerobic environments? Complex microflora existed on Earth at least 3.5 b.y. ago. Was the earliest atmosphere strongly reducing? What initial states and evolutionary histories produced such different physical/chemical final states as the present atmospheres of Mars, Earth, and Venus? The isotopic composition of Xe in the terrestrial atmosphere is profoundly different from that in other known solar system reservoirs: the solar wind (does this really represent the sun?) and the meteorites. The difference apparently results from a gross mass fractionation. Could this be a consequence of an early, almost total loss of primitive atmosphere, or is this an inherited signature from operation of some fractionation mechanism in preplanetary matter?

(10) Present-day Partitioning of Volatiles among Mantle, Crustal, and Atmospheric Reservoirs; Extent and Chronology of Outgassing, and Implications for Thermal History

To what extents are the Earth and other terrestrial planets outgassed: i.e., what fractions of their initial inventories of volatiles reside in atmospheres or have been lost to space? What are the chronologies of outgassing: e.g., early catastrophic, and if so when and by what mechanism? The short half-life I-Xe, Pu-Xe and long half-life K-Ar radiometric chronometers are currently the most promising probes to terrestrial outgassing history, but the important modeling parameters such as paleoatmospheric Xe and Ar isotopic compositions, and present-day Xe and Ar isotopic compositions (and I and K concentrations) in the mantle are unknown or slightly known. Are there discrete, isolated mantle reservoirs of volatiles? Are they identical in space and time to the basaltic source region reservoirs?

II Physical and Chemical Evolution

Introduction

This topic is sufficiently broad to include nearly all aspects of planetary formation, evolution and present state. We will restrict our attention to the physical and chemical processes that govern the evolution of the bulk of the planet after its formation. Although they are recognized as important, the details of planetary condensation and formation are left to the working group on planetary formation.

Problems

The basic problem is understanding how a recently condensed and accreted planet redistributes heat, mass, accretional energy and chemical species, and how these processes influence each other and the final state of the body.

(1) Questions Regarding the Initial State

(a) The distribution of material resulting from accretion—substantial lateral (as well as radial) heterogeneities might lead to earlier overturn and mixing or further differentiation as denser material sinks to the center. Did substantial mixing take place during accretion?

(b) The initial energy budget—the temperature distribution, as well as density distribution that may influence the temperature through such processes as core formation.

(c) The initial bulk chemistry—the concentration of heat sources, including short-lived isotopes, the abundance and distribution of volatiles, the existence of possible core phases and of early crustal material.

A major expansion of our knowledge of the physical and chemical evolution of the Earth and planets is occurring because of: (1) the application of high precision isotopic analysis to questions of the nature, duration, and transfer of mass between reservoirs; (2) the development of transient and, particularly, static very high pressure experimentation (diamond anvil cells) and application to hitherto unexplored regions of P-T-X space corresponding to planetary mantles and cores; (3) the application of increasingly sophisticated techniques of experimental petrology and trace element modeling to petrogenetic problems; (4) the development of parameterized convection calculations leading to an advance in understanding the transport of heat.

(2) Isotopes

The identification of several distinct isotopic reservoirs which communicate with the Earth's surface, one of which has remained approximately chondritic over the age of the Earth, raises many questions for study. For example:

(a) Why has the Earth evolved differently from the Moon with respect to isotopic systematics? Is it possible to develop our understanding to the point that we might predict the "style" of evolution of other planets prior to a sample return?

(b) Is the Earth's "chondritic uniform reservoir (CHUR)" really chondritic? If so, what are the implications of non-chondritic mutually-normalized REE patterns in chondrites for planetary assembly? Would we expect the Moon and other planets to have CHUR's?

(c) What are the present-day isotopic structures of the Earth and Moon, and how and when did they achieve their present status?

(d) How much of the mantles of the Earth and Moon have contributed to mass in their crusts and atmospheres? Are inferred masses of reservoirs and time scales for mass transfer consistent with

deductions from heat flow, convection calculations, seismology, gravity, and electromagnetic measurements?

(e) What are the relative ages of the Earth, Moon, and meteorites?

(f) What is the relative importance of planetary size versus chemical composition (core size, H_2O content) in determining the time scales and styles of physical-chemical evolution?

(3) Very High Pressure Experimentation

The development of diamond anvil technology is leading to a rapid increase in our knowledge of the behavior of material at high pressures and temperatures. Questions include:

(a) How do elements partition between "unquenchable" high pressure phases? Is the Earth's lower mantle in equilibrium with its upper mantle and core? What are the implications for the concept of a post-core-formation separation of the Moon from the Earth?

(b) Could disproportionation reactions with subsequent differential mass transfer of oxidized and reduced species be responsible for the relatively oxidized state of the Earth's upper mantle and the reduced state of the core? How does this question bear on the range of oxidation states observed among lunar and meteoritic basalts where disproportionation reactions in parent mantles were probably unimportant?

(c) What is the influence of very high pressure reactions in the transfer of heat in the Earth and planets?

(4) Petrogenesis

The developing synthesis of our concepts of the natures of the upper mantles of the Earth and planets leads to a number of problems. For example:

(a) Do phase assemblages exist in Mars and Mercury which are absent within Earth, Venus, and Moon and which are unexplored experimentally? What would be the nature of magmas produced in such source regions?

(b) Are petrogenetic models based on trace elements consistent with our understanding of phase equilibrium from experimental petrology and of physical environment as deduced from geophysics? Is the evolution of magma on each planet due to distinct processes, or simply due to our inadequate knowledge of the necessary parameters of the same process?

(c) Is H_2O necessary for plate tectonics to exist? Does that mean that the Venus mantle is dry? What is the objective evidence that H_2O has not played a role in lunar petrogenesis?

(d) Do some igneous meteorites come from presently existing planetary bodies? If so, we would have an idea of planetary petrogenesis in the absence of direct sample return.

(e) Do komatiites represent high fractions of melting and, if so, does that imply that higher heat flow in the past dominated Archean petrogenesis? Are there komatiites or their equivalents on the Moon and other planets?

(f) By what physical mechanisms do magmas ascend to the surface?

(g) Are magmas on H_2O-bearing planets reliable indications of the oxidation states of their source regions, presumably planetary mantles?

(5) Mass Transport

The mode of transport of chemical species within a planet is central to planetary differentiation and evolution. Large-scale advection can move material about, but transport to or through the surface requires other processes. Escape of volatiles, magma migration and eruption may be the most important near the

surface. Is material deep in a non-molten planet transported by diffusion along grain boundaries or by small amounts of a fluid phase? How can remixing of different materials occur? Are solid-state diffusion processes too slow? Does vigorous convection and heat transport lead to more homogeneity or facilitate differentiation and layering? How can distinct isotopic reservoirs exist even though they all communicate with the surface? Does their existence imply a physical separation such as layered convection?

(6) Thermal Modeling

The discovery that simple models of vigorous convection can be analyzed has led to major advances in modeling the thermal history of planets. The models are based on systematic, asymptotic relations between the Rayleigh number and Nusselt number (dimensionless heat transport) for a convecting layer, which have some experimental support. Questions that remain are:

(a) What is the effect of a strong lithosphere on the heat transport?
(b) Is heat transport controlled by fracturing and rifting (i.e., the strength of the lithosphere) or by deeper seated processes?
(c) Is it possible to model layered convecting systems?
(d) Can models include nonsecular time variations (e.g., oscillations)?
(e) What is the effect of redistribution of heat sources?

III Surface Processes

Introduction

An understanding of the evolution of early planetary crusts necessarily involves knowledge of early surface history. Overall objectives are to assess major terrain types, topographies and surface characteristics of the terrestrial planets as indicators of the nature of early planetary crusts and to determine the effect of surface processes on the evolution of primary crustal materials. Surface processes fall into two classes: (i) those largely unique to a planet, such as climate, interactions of crusts with atmosphere, hydrosphere and biosphere, and (ii) those common to all planets, such as volcanism, interactions with interplanetary bodies and solar materials. The former are of greatest importance for highly active planetary bodies, particularly the Earth. In contrast, the latter are important to planets with poorly-evolved crusts, such as the Moon and Mercury. Mars and possibly Venus represent intermediate states and form an important bridge between the classes of surface processes.

Problems

The following problems and objectives, although not inclusive, are of particular importance to understanding surface conditions and processes on early planetary crusts.

(1) Climate

A critical parameter affecting the surface character of a planet is its climate, particularly surface temperatures and evolution of atmosphere.

(a) Surface Temperatures: The oxygen isotopic composition of Archean cherts have suggested surface temperatures on the order of 70°C at 3.4 b.y. for the Earth. If correct, this constrains models for the luminosity history of the sun and/or the evolution of the terrestrial atmosphere, matters of paramount importance for *all* planets. A better understanding, however, is required of oxygen isotope ratios in silicified sediments before this temperature can be considered firm.

(b) Arid or Humid Atmosphere: The moisture content of early atmospheres relates directly to the temperature history and the water cycle of an evolving planet. Many aspects of sediments are indicative of climate conditions. Sedimentologic analyses will supply qualitative information on the overall arid or humid character of the Archean atmosphere on Earth. Detailed examination of evaporite sequences is particularly encouraged with respect to the Earth. Additional constraints of variations in the water cycle are available from imagery of Mars, where periods of periglacial, fluvial and eolian sedimentation are indicated.

(c) Composition of the Atmosphere: A reducing atmosphere for the early Earth has recently been challenged. A more detailed mineralogical and geochemical investigation of Archean iron-bearing sediments and Archean weathering profiles is required to resolve this question, as well as place constraints on the relative levels of other atmospheric constituents. Degassing models for the other terrestrial planets are available. These models should be constrained by information derived by analysis of early sediments on Earth. Conversely, early Archean sediments should be examined for evidence of interaction with atmospheric constituents predicted from degassing models.

(d) Composition of the Hydrosphere: This is of importance only to the Earth, with the composition of the early hydrosphere inferred from the record preserved in Archean chemical sediments. Systematic studies of the composition of carbonate rocks, cherts, and sulfates have revealed first order (10^8–10^9 years) secular changes in isotopic composition coupled with second order (10^6–10^7 years) fluctuations. Additional studies are required, particularly with respect to light $\delta^{18}O$ in Archean sediments, which may indicate higher temperatures or a different seawater composition at this time.

(2) Interaction of the Crust with the Atmosphere, Hydrosphere, and Biosphere

This problem area is of particular significance to the Earth, Mars and Venus.

(a) Nature of Weathering: The Archean hydrosphere and atmosphere and associated low-temperature alteration influenced the composition of sedimentary products and was a major factor in establishing ocean chemistry on the early Earth. The mineralogy and chemistry of the sedimentary products of water-rock reaction, in particular submarine weathering profiles, will yield data on shale genesis, the temperature of Archean oceans, and chemical gains and losses within the hydrosphere. Analysis of terrigenous sediments will yield information on atmospheric weathering processes. As samples are not available, experimental and theoretical analog studies will be required to assess early weathering processes on Mars and Venus.

(b) Hydrothermal Alteration of Crustal Material: Hydrothermal fluids are conventionally believed to be heated surface waters, circulating in the upper crust as well as metamorphically-generated fluid released by prograde metamorphism. Study of the reaction products on Earth can provide an insight into the physical and chemical nature of these fluids, the dimensions of the thermal regime, and establish the temporal and spatial role of high-level plutonic bodies in providing heat energy. Stable isotope and petrochemical studies will provide a broad data base for these investigations. Analog studies will again be required when considering the other terrestrial planets.

(3) Sedimentation

Sediments provide information on physical processes operative within and chemistry of water bodies on planetary surfaces. The Earth is the major data source and may provide analogs for understanding sedimentation on Mars. Impact sedimentation is considered separately under problem (4).

(a) Archean Provenance Terranes: Sandstone petrography and shale geochemistry are necessary to characterize the composition of Archean provenance terranes. Studies are available for a few occurrences, but are required from various areas to provide information pertaining to such problems as the earliest development of granites and the nature of the early crust on Earth.

(b) Physical Processes and Depositional Environments: Archean metasedimentary sequences bear strong resemblance to modern counterparts and it is likely that early environmental conditions were not significantly different from those of today. Documentation of lithologies, sedimentary structures, and vertical sequences are required for interpreting the operative physical processes. Paleoenvironments reconstructed from these investigations will provide the framework for understanding the origin of the earliest terrigenous sediments.

(c) Chemical Sedimentation: The paleoenvironments of chemical sediments in the Archean are virtually unknown. These chemical deposits are important since they can constrain the composition, temperatures, p_{O_2}, and pH of the water in which they precipitated. These rocks are also the most likely host rocks for early fossils, and they may be one of the most sensitive indicators of surface conditions on the early Earth.

(d) Tectonic Implications of Land-Sea Relationships: Terrestrial sediments imply land emergence. Documentation of the global distribution of such sediments will indicate the extent of emergence. Lateral and vertical associations of paleoenvironments reflect the tectonic setting of the depositories. Thicknesses of sedimentary sequences will constrain models of lithospheric thickness. These investigations are also relevant as to when the Earth's surface developed a topographic bimodality.

(4) Impact Processes

All the terrestrial planets underwent a period of early intense bombardment by interplanetary bodies. The effects of impact are most evident on the Moon and Mercury. Although no evidence of

this high impact flux is preserved on Earth, the possible effects on early Archean crustal evolution must be considered by analogy with other planets.

(a) Flux of Impacting Bodies: The Moon is the source for establishing the temporal variation of the impact flux, indicating an early flux ratio at least 1–2 orders of magnitude greater than the present day. Some interpretations also indicate a singular, short-lived period at 3.9 ± 0.1 b.y. during which impact by planetesimal-sized bodies produced the majority of the $\sim$1000 km-sized multi-ring basins. Inasmuch as basin-sized impacts account for the bulk of the exogenic energy deposited on early crusts, cratering chronology must be re-evaluated to determine whether the so-called "lunar catacylsm" is a real or apparent event and whether it is relevant to the Earth and other bodies.

(b) Effects of Impact: Basin-forming impacts on the Moon created major surface topographies, crustal compositional inhomogeneities, localized thermal anomalies and are major erosional and depositional forces. These data have to be applied to other planets, such as the Earth, having been adjusted for differences in variations in impact conditions, planetary gravity, presence of atmosphere or hydrosphere, etc. The long-lived thermal effects of impact must be modeled, accounting for variations between planets in crustal and lithospheric composition and thickness. Only by constrained models can the relative importance of exogenic processes on crustal and surface evolution be assessed for the various terrestrial planets.

(c) Morphology and Morphometry: Impact craters exhibit a morphologic and morphometric variation with size. Superimposed upon this basic progression are variations in crater form and ejecta characteristics, which provide information on the physical nature of the target substrate. This problem area is of specific relevance to Mars, which exhibits the greatest variation in crater-forms of all terrestrial planets, presumably due to variations in a volatile-rich layer in the substrate. Differences in crater form must be thoroughly evaluated. Through analog and experimental studies they will provide basic information on the nature of early surfaces of planets which have not been sampled directly.

(5) Volcanic Processes

Volcanic activity played a major role in the generation of early crustal materials. Ample evidence exists for widespread early volcanism on Mars and the Moon and it is likely that similar activity occurred on Mercury and Venus. Volcanism in the Archean of the Earth is considered in detail under section VI Crustal Features and their Development.

(a) Style of Volcanism: It is not clear if present terrestrial eruptions are good analogs for the volcanic processes which produced the vast lava plains of Mars, infilled the lunar basins, or created the plains units of Mercury and Venus. Flood lavas comparable to the Deccan Traps may be equivalent but the other planets may illustrate a volcanic style not seen on Earth since possibly the early Archean. Explosive activity may have been important on planets other than the Earth, and may provide information on volatile sources on other bodies. The volcanic style likely to occur in the high temperature/pressure environment on Venus is poorly understood and must be modeled.

(b) Duration of Activity: Discrete pulses of lava emplacement, with hiatuses of $\sim$100 m.y., are evident for lunar basin infilling. On Mars, lava plains were created over large areas of the planet during an extended interval of $\sim$2–3 b.y., but toward the end of this period a diverse range of volcanic activity resulted in the formation of numerous constructional features. The processes which caused these temporal and spatial variations in activity are unknown, but relate to the thermal and tectonic evolution of each planet. Detailed mapping of observed volcanic materials and numerical modeling of possible eruption mechanisms on these and other planets will consequently provide important constraints on mantle-crustal evolution.

(c) Indirect Consequences: This subject is poorly understood, even for the Earth. The interaction of erupted material with particular atmospheres such as on Mars and Venus is not known. Volcanic activity itself may cause significant changes in atmospheric composition and an appreciation of volcanism over

extended periods of time is relevant to crust-atmospheric interactions. Indirectly produced landforms must also be considered. For example, on Mars giant mud flows and fluvial activity generated by magma encountering subsurface volatiles may have radically affected the surface terrain.

IV Planetary Formation

Introduction

The influence of formation circumstances on early crustal genesis is most strongly indicated by lunar and meteoritic radioisotopes. The lead isochron for highland rocks requires crustal differentiation to be essentially completed more than 4.4 b.y. ago, but distinctly later than the Rb-Sr model age of the lunar soil, 4.60–4.65 b.y. The crystallization ages of differentiated meteorites are nearly all greater than 4.0 b.y., and are predominantly greater than 4.4 b.y. The Pb radioisotopes of the Earth also suggest early activity, their simplest (but not unique) interpretation being core formation 4.45 b.y. ago.

The ages of these earliest rocks require energy sources other than the long-lived radioisotopes, U, Th, K: most obviously, gravitational or collisional energy, but also possible electromagnetic effects or short-lived radioactivity from ^{26}Al. The latter effects may be particularly significant for meteorite parent bodies, which were likely too small to suffer high enough collisional velocities for the heating. The magnitudes of these energy sources are all strongly dependent on circumstances of planetary formation.

The formation of the terrestrial planets (including differentiated meteorite parent bodies) is a part of the much larger problem of the origin of the solar system. Manifestly, the formation of the inner solar system bodies must be a by-product of solar and major planet formation. The influence of solar formation is most evident through the dearth of volatiles in the terrestrial bodies. The influence of major planet formation is most evident through the existence of the asteroid belt in place of a planet, and the smallness of Mars. Solar formation is in turn a part of the problem of star formation. A complete understanding of terrestrial planet formation would necessarily entail a solution of this hierarchy of problems. However, as discussed by Wetherill (1980), there are some theoretical investigations and data interpretations which pertain mainly to formation of the terrestrial planets, and therefore to early crustal genesis. Logically included in this discussion are aspects of planetary evolution which were very likely underway well before completion of planetary formation, such as core separation and outgassing.

The scientific investigators whose work pertains to terrestrial planet formation include those concerned about:

- Dynamics of large-n body systems in orbit around a massive primary;
- Physics of large impacts;
- Models of planetary thermal and compositional evolution;
- Interpretation of differences in bulk composition (including isotopic evidence) among the terrestrial planets, asteriods, and meteorites;
- Properties (physical as well as petrological) of differentiated meteorites;
- Nature of the early solar wind and planetary magnetic fields.

Among workers on these topics there are identified problems ranging in character from the highly technical and intradisciplinary to the predominantly communicative and interdisciplinary. The emphasis of this summary will be on interdisciplinary character and relevance to crustal genesis.

Problems

(1) What were the Agglomerations Earlier than the Terrestrial Planets, and their Influences on the Subsequent Planetary Formation?

The answer to this question is needed to explain the great ranges in size, composition, and dynamical properties of the planets, and to deal with the complexity of the variety of hypotheses of initial agglomeration and subsequent interaction, including disruption, as well as growth, of bodies. While the terrestrial planets must have formed from an aggregation of grains or small bodies, the dynamical history of these bodies appreciably affected their masses, chemical compositions, and velocities. This dynamical history must have

included a variety of interactions among planetesimals, protoplanets, and gas. The efforts of a few researchers are directed specifically at these problems, but much of the relevant current progress pertains to quite different dynamical problems such as planetary rings, resonant orbiting systems, stellar accretion disks, galactic structure, plasmas, and molecular systems.

Ten years from now the dynamical questions about solar system origin will probably be similar. But there will be some shifts of emphasis resulting from the identification and solution of certain theoretical problems. A foresighted program will support dynamical research on models which are simplified and abstract compared to what must have been the solar nebula and protoplanets. However, the soundest progress in building the relevant physical understanding will come from the solution of these solvable problems.

(2) What was the Phasing of the Loss of Volatiles from Terrestrial Planet Material?

The classical evidence was that the similarity of the Earth and meteorites in primordial depletion of the five inert gases—orders-of-magnitude greater than active gas depletions—required that the volatiles were lost not later than when the Earth material was incorporated in bodies of similar size to the meteorite parent bodies. But rigid enforcement of this condition requires a mode of formation for the terrestrial planets different than that for the major planets. It is also arguable that the classical data are scattered enough that the losses from planets could be by different mechanisms than from meteorites. This assumption (unfortunately implicit) has been made by Cameron, Ringwood, and Hayashi and their respective co-workers. All of these models entail, in different ways, separation of volatiles and refractories in massive protoplanets and subsequent loss of volatiles by some sort of solar effect, abetted in some cases by collisions or interaction with the nebula. The presence of a gaseous nebula of appreciable mass would have had significant dynamical effects as well, ranging from loss of small bodies by drag to secular resonance effects on planetary orbits.

The findings of planetary exploration as to inert gases have added further puzzles. The enormous differences in $^{36+38}$Ar abundance among (in ascending order) the Moon, Mars, Earth, and Venus appear to arise from circumstances of origin, but the explanations offered so far are most charitably described as *ad-hoc*.

Interrelated with the problem of volatile loss is that of volatile acquisition. The positive correlation of volatile abundance with planetary size suggests an increasing volatile content with time of the material acquired by a planet: either from the nebula or from planetesimals scattered from the outer solar system.

The planetary volatile problem will probably still be very much around in ten years, because it depends on a combination of nebula evolution, planetary heating and differentiation during accretion, and the retentivity of volatiles in solids. However, there are some fairly specific problem areas, such as theoretical models of hot atmospheres and their interaction with impacts, or experimental determination of mechanisms of retention of inert gases in silicates, on which perceptible progress should be achievable.

(3) What are the Principal Factors Affecting the Bulk Compositions of the Planets?

This topic overlaps that of volatile gain and loss, of course. However, there are variations in the relative abundances of calcaluminous silicates, ferromagnesian silicates, reduced iron, and trace elements which appear to arise from quite different effects. Most notable are the marked iron enhancement and depletion in the two smallest and driest bodies, Mercury and the Moon, respectively. Such great variations among materials of similar condensation temperature suggest differentiation in planetary interiors followed by removal or breakup and some sort of selection mechanisms, probably dynamical. These processes must have been quite different for Mercury and the Moon, which in turn underlines that the lesser variations among the Earth, Venus, and Mars will be difficult to ascribe with certainty to a systematic model.

At present, the variations in bulk composition from predictions of condensation models appear to be attributable to dynamical effects, and hence overlapping in their explanations with problem (1). These effects may range from gas drag on centimeter-size particles to impacts of Mars-sized bodies into proto-Earth or proto-Venus. The small-body end of this spectrum should be amenable to systematic attack, but the large end will remain like "The Ten Little Indians" ending at four (or rather five, since this scenario has births as well as deaths); the final big collisions were probably too different to be treated as a systematic class.

(4) What was the Heterogeneity of Infalls into the Terrestrial Protoplanets?

It appears almost certain that infalling planetesimals had a great range of sizes, with the bulk of the mass in the larger bodies. The uncertainty is mainly the upper end of this mass spectrum due to the competition of agglomerating and disrupting effects (such as tidal). In any case, the upper end in the later stages was at least 100-km bodies. Hence heating and mass movement in a forming planet almost certainly was sporadic with great lateral variations. An important consequence of the bulk of the mass being in the larger bodies is that most of the delivered heat would have been buried, rather than lost by radiation or ejecta. This heterogeneity in size with most of the mass in large bodies appears to be characteristic of all current alternative dynamic models.

More uncertain is the degree of heterogeneity in composition; the same factors causing variations in composition among planetesimals. Of interest, but quite speculative at present, are the sizes of iron agglomerations among the planetesimals, which would have stimulated core formation. (However, this may not be a problem, if iron conglomerations are normal consequences of sizeable magma accumulations which are oxygen-deficient.) The larger-scale heterogeneity of a trend from more refractory to more volatile composition in the infalling matter is dependent on the evolutions of temperature and interzone mixing in the nebula. Hence, for some time it will be constrained more by compositional inferences from data—planetary, asteroidal, and meteoritic—than by physical models. Better models of compositionally associated effects of impacts, mentioned under problem (5), would be of help on this problem.

(5) What are the Effects of Great Impacts?

Photogeologic examination of the Moon indicates positive correlations of the amount of melt and the size of secondary craters with the size of primary craters. These correlations confirm physical considerations that the portion of energy going to heat and the size of fragments increase with the size of an impacting body at a given impact velocity. Most of the mass in planetary formation probably came in bodies appreciably larger than that which created Mare Imbrium. Hence, probably more than half the energy of impacts was retained as heat within the forming planets, providing ample energy for crustal differentiation and raising the temperature high enough for core formation well beyond completion of growth.

It is desirable to quantify these effects for cosmogenic problems; perhaps not so much for planetary formation (where significant heating seems like a sure thing) as for planetesimal heating, where the energies of impact were more comparable to those occurring later in planetary cratering. This work is necessarily an extrapolation by computer modeling, to be undertaken gingerly in view of the expense of available codes. An important extension of this work which should be undertaken when monocompositional impacts are better understood is the effect of volatile content, in view of its differing expansion upon vaporization.

(6) What Energy Sources were there aside from Impacts?

A problem still with us is the melting of meteorite parent bodies. The sizes indicated by cooling rates inferred from Ni:Fe gradients in iron meteorites are small enough to make it implausible that the energy was collisional, since impacts energetic enough for melting are also sufficient to overcome the gravitational binding energy. Alternatives suggested are electromagnetic induction and short-lived radioactivity: ^{26}Al.

Both processes depend on nebula properties and their evolution. Induction further depends on solar magnetic field intensity and structure, while short-lived radioactivity depends on the amount and distribution of material injected rather late in nebula formation, and on the timing of planetesimal agglomeration. They are all rather speculative modeling problems, but meteorite evidence in the coming decade may further constrain the problems of Al abundance and timing of planetesimal formation.

(7) What were the Influences of Planetary Formation on Planetary Evolution?

It is likely that all the major evolutionary processes—core formation, outgassing, and crustal genesis—were underway in proto-Earth and proto-Venus by the time they had reached one-tenth their final masses: i.e., Mars-sized. Mercury also had sufficient energy for early differentiation because it was close to the sun, while the Moon had it by virtue of being a satellite. On the other hand, Mars may not have received a similar early pulse of energy because as its mass approached its present value its zone had been depleted of planetesimals by Jovian dynamical effects.

The total energy available for heating and differentiation of terrestrial planets prior to 4.4 b.y. ago probably was much greater than the total since then (other than for Mars). The rate of infall of planetesimals dwindled rapidly. While it continued sufficiently to garden the surfaces appreciably, reset radiochronology, and make Imbrium-sized features occasionally, the averaged energetic rate was small compared to the long-lived radioactivity. Core formation, once underway, almost certainly went to a catastrophic conclusion, because of the great stresses set up in the silicate center by any asymmetry.

Hence, for planetary evolutionary models it is plausible to assume a transition from exogenic to internal energy sources not later than 4.4 b.y. ago, with mean temperatures close to melting throughout the body at that time for bodies which have cores. This temperature curve would be the reasonable consequence of the strong temperature dependence of viscosity, leading to the removal of heat in excess of melting at an *averaged* rate fast compared to the *averaged* rate of input from infalls in *most* models—but not all: particularly not lunar, if the Moon was created by major impact in the Earth.

The magnitude of lateral heterogeneities prior to 4.4 b.y. ago must have been considerable, contributing greatly to heat removal and *both* differentiation and mixing. Just how the activity decreased subsequent to 4.4 b.y. ago in bodies larger than the Moon is rather debatable, because of the obliteration of the record in the rocks and the reduction of temperature differences among different initial models due to the temperature dependence of viscosity. But it apparently took a lot of shuffling around before pairings of pieces of crust with lithophile and iron depleted upper mantle allowed the stabilization of cratons.

Plainly more thought and interaction is needed on the nature of early evolution growing out of planetary formation and its influence on crustal genesis and craton stabilization. Problems which may yield some constraints are the need to inhibit interaction of the core with late-infalling volatiles and variations in isotope ratios among rocks more than ~3.0 b.y. old.

Because of the indirectness of the inferences, constraints on early Archean events from formation circumstances will require appreciable modeling. The relevant capability now works mainly on mantle convection in the Phanerozoic; the appropriate framing of problems may lure some of it over to the Archean. Therefore, interactive conferences, etc., should be considered and good proposals on these problems supported.

V Metallogenesis

Introduction

Although the general features of Archean mineral deposits are well known, we do not have a detailed understanding of how their origin may fit in with the broader aspects of the early evolution of Earth's mantle, crust, hydrosphere and atmosphere. A goal of this working group will be to develop an understanding of the Earth's earliest metallogenic processes in a planetary context in such a way as to be able to make first-order extrapolations about possible similar processes on other terrestrial planets.

Planetary Scale Problems

(1) What were the primordial abundances of ore elements in the proto-Earth and the other planets, relative to solar/meteorite abundances?

(2) Can abundances of ore elements in the surface layers of other planets be predicted from assumed primordial abundances and known geochemical properties of the ore elements? For example, if siderophile elements are concentrated in cores of planets with Fe-Ni cores, would siderophiles be more abundant in the outer portions of planets with Fe-S cores, such as Mars?

(3) What are the implications of the *rate* of core formation for the present distribution of ore elements? If core formation was slower than usually assumed for Earth, would this concentrate siderophile elements in early crusts of planets?

(4) What ore-forming processes are likely to be planetary rather than simply terrestrial? Is it likely that impacting could give rise to conditions favoring ore deposition (e.g., Sudbury)? Can volcanism *per se* lead to conditions favoring ore deposition in the absence of an H_2O volatile phase? Are there any mineral deposits conspicuously associated with *rifting*? What kind of mineral deposits might be formed in a planet (Venus) where CO_2 is the dominant volatile phase?

(5) If cumulates exist, how might their formation be influenced by different gravitational fields on other planets? More generally, how do different physical conditions on planets affect magmatic processes?

(6) Given the small planet model for the origin of asteroids and meteorites, what ore metal distributions might have taken place within such small bodies? (Implications for space industrialization.)

(7) How do ore element abundances relate to models for formation of Earth and planets? Does abundance of volatile elements (e.g., Pb) indicate late-stage accretion of volatile phases in the outer Earth?

Terrestrial Problems

1. What is the nature of metallogenic provinces? For example, do Bolivian and Malaysian tin deposits indicate an ancient mantle tin anomaly? Do African chromites indicate a mantle chromium anomaly? Can we relate such provinces to other geochemically or isotopically distinct regions?

2. Has there been a fundamental change in ore forming processes through time, or do ancient ore deposits merely reflect the chance preservation of unusual environments? For example, does the abundance of Archean gold deposits indicate something profound about abundance of gold in early Earth, or does it mean merely that more heat sources around at that time led to more gold deposition in workable amounts?

3. How do sites of ancient mineralization (e.g., in Archean greenstone belts) compare with modern equivalents, e.g., island arcs, back arc basins? Are the ancient ore deposits identical with those forming today?

4. Was ore deposition in crustal rocks through time affected by the major crust forming episode indicated isotopically to have taken place 2.5–3.0 b.y. ago? Are ore minerals recycled through ocean sediments into the mantle, or is it a one way trip? What can we say about present mantle destruction of ore

elements? Was the upper mantle effectively depleted of ore elements by 2.5–3.0 b.y. age, and if so, which elements? Are there elements being removed directly from mantle at present, e.g., copper at porphry copper deposits, or are the metals extracted from older oceanic crust?

5. What is the *primary* origin of metals in oceanic hydrothermal mineral deposits?

6. What processes led to concentration of metal such as Sn and W in ancient pegmatites? Are early pegmatite minerals similar worldwide or do definite provinces exist?

7. Can different mineral provinces in the Canadian shield be related to differences in tectonic setting of crustal fragments concerned? How does distribution of ore deposits in ancient cratons relate to what is known of ancient sutures, plate margins, etc.? Does the evidence that sutures in North America influence mineralization over long periods of geologic time apply to other areas?

8. Can changes in mineralization patterns through history be matched with other known petrological processes, e.g., increase in crustal K_2O/Na_2O 2.5–3.0 b.y.?

9. What were P-T conditions of important Archean ore deposits, e.g., chromites, and what are the nearest analogs today?

10. How has atmospheric evolution affected ore deposition, e.g., was there a change from reducing to oxidizing? Did it affect banded iron formations and ancient uranium?

VI Crustal Features and Their Development

Introduction

The basic sets of planetological data on which theories, models and processes for crustal development are based include: regional tectonic patterns, geologic field relations (rock types and structures), petrology (minerals and textures), geochemistry (major and trace elements and isotopes), geophysics (magnetism, gravity and density), and chronology (relative and absolute). The data that characterize crustal features and their development are derived primarily from the Earth but also, in substantial amounts, from the Earth's moon. Other much more limited spectral, geophysical and imagery data exist for the crusts of Mars, Venus, Mercury and some asteroids. Some meteorites that may represent crustal materials from asteroids or other planets can also contribute to the data sets. Because the problems of characterization are best defined for Earth the following discussion is primarily Earth-oriented with the Moon and other planetary bodies included briefly.

Problems

(1) The Earth's Crust

The Earth problems are outlined under four categories.

A. Rock Compositions: Their Volumes and Secular Trends

(a) General features and implications:

Much attention has been focused on the delineation of *time trends in rock abundance* (volumes). The Archean is characterized by a paucity of K-granites, alkali basalts, basic dikes, and carbonate sediments; by an abundance of tonalites and by a virtually unique development of ultramafic komatiites and calcic anorthosite complexes. Most of the major deposits of Ni, Au, and Pt are of early Precambrian age. Cherty iron formations are essentially restricted to Archean and Proterozoic terranes. Granulites also are primarily of early Precambrian age. Although depth of erosion is a factor to be considered as the cause of some of these trends it is more likely that these features are genuine characteristics of the Precambrian crust.

Changes of bulk chemical concentrations in the crust with time have been claimed by various authors. These changes have commonly been documented by the study of sedimentary materials that integrated the various crustal components through weathering and erosion. Some of the reported trends include increasing K/Na, rare-earth element concentrations and $^{18}O/^{16}O$ but decreasing Fe^{2+} and Mn^{2+} from the Archean through the Proterozoic. In addition, there is the development of a negative Eu anomaly and an enrichment of light over heavy rare-earth elements during this same period. Some of these trends in sediments show their most marked changes at about 2.5 billion years ago, the Archean-Proterozoic boundary, as does the $^{87}Sr/^{86}Sr$ ratio which rises very sharply at this time after following a mantle trend to this point. In an overall trend the Archean crust appears to have been more mafic than its younger counterparts. The nature of the earliest continental crust, which is not preserved or yet identified may be usefully determined in part from the composition of the earliest sediments such as at Isua, Akilia, Barberton, and Pilbara.

The more general problem of how much recycling has taken place between crust and mantle through geologic time has been the subject of many papers. Isotopic data has been a major component in the arguments. Proponents of extensive recycling have encountered strong opposition from advocates of the view that crustal material is never subjected to rehomogenization in the mantle. The crux of the question is whether the bulk of the present

continental crust was formed during the Archean or whether there has been a longer term evolution of the crust. These arguments concern the controversial problem of recycling of continental crust, in large part as sedimentary material.

A fundamental problem of the evolution of the continental crust is the widely agreed upon change that took place during the transition from Archean to Proterozoic. This concerns not only the change in rates of radiogenic isotope production and abundance of chemical components but also the increasing stability of the crust (as evidenced by development of aulocogens, shelves, alkaline complexes, dikes, and kimberlites), the decrease in volcanic activity (especially oceanic type), the appearance of continental margin-type orogenic belts, the development of stable continental interiors, and the occurrence of continental margin-type geologic units (Coronation geosyncline and other Wilson cycle type units).

(b) Greenstone belts:

i) Nearly unique development of ultramafic and basaltic komatiites. What is the regional distribution of komatiites? Has there been modification of primary liquid compositions by later alteration? What are the implications for the nature and extent of partial melting in the Archean mantle, for heat flow in the Archean, and for other aspects of mantle evolution?

ii) Mafic lavas versus andesitic calc-alkaline lavas. What are the regional distribution and relative proportions of each type? What are the tectonic implications of the belts? What chemical interactions comparable to modern basalt-seawater reactions have modified subaqueous lavas? What are the implications for partial melting in the mantle and recycling of crustal materials?

iii) Scarcity of alkaline rocks. Why are there so few alkaline rocks in greenstone belts? What are the implications of the few that do occur as in Manitoba and Ontario?

iv) Nature of sediments. How do the chemical compositions of the clastic sediments vary within and between greenstone belts? Do they represent bulk samples of continental crust? What are the implications for overall continental crustal properties during the Archean?

v) Variations between greenstone belts. What differences exist in the abundance of various volcanic lava types and sediments between greenstone belts of the same age and of various ages? What are the implications for temporal and lateral variations in the tectonics of greenstone belts?

(c) High grade terranes:

i) Tonalites. Metamorphosed and deformed tonalites provide information on the character of the lower crust during the Archean. In what tectonic environments did the tonalites form and later deform into gneisses and granulites? What regional variations exist in the chemistry of tonalitic rocks? More information is needed on the trace element composition of the granulites and on the composition of their fluid inclusions to provide constraints on the origin of the granulites and the chemical transfer mechanisms that are involved. Through the study of isotopic systems more accurate estimates should be developed for crustal residence time of various tonalitic components, for the extent to which the tonalites represent reworked earlier crust, and for the nature of accretional patterns (episodal, continuous, or instantaneous).

ii) Volcanics. How did volcanic rocks get into the high grade environment of the lower crust? What was the nature of the initial melts from which the metavolcanics were derived? There are some indications that the metavolcanic sequences may have contained tholeiitic basalts and some komatiites. What is the trace element chemistry of these metavolcanic amphibolites?

iii) Plutonics. What is the chemical composition and environment of formation of anorthositic through leucogabbroic and ultramafic through gabbroic complexes that are often associated with metavolcanics? What differences are there, if any, between these complexes in high grade terranes and in greenstone belts?

iv) Metasediments. How did the sediments get into the high grade environment of the lower crust? The metasediments commonly consist of marbles, quartzites and schists. Much chemical and isotopic work is needed on them. How well do their current compositions represent their initial composition? What do they tell us of the bulk sampling of the crust from which they were derived?

v) Variations of high grade belts. What is the nature of variations within and between the high grade belts? What is the meaning of the variations in terms of original igneous zonation, level of exposure, and superimposed metamorphism?

B. Structures and their Tectonic Significance

Arguments have been made in favor of Archean crustal structures being largely a result of horizontal processes such as lithospheric plate movements while other arguments have favored largely vertical processes such as diapirism, downsinking, or rifting. In some arguments the horizontal tectonics are associated primarily with greenstone belts and the vertical tectonics with gneiss terranes. Still other arguments suggest that both horizontal and vertical tectonics have affected the same parts of Archean crust but at different times or different depths.

More study should be devoted to the relative importance of downsinking, diapirism, and lateral compression in greenstone belts. These have important implications for tectonic models of greenstone belts. What is the tectonic significance of the thrust-nappe stacking which is thought to have taken place in several high grade terranes? Quantitative estimates are needed for the relative displacement across faults and shear zones that separate crustal blocks of different types.

C. Growth of Continental Crust

It has been argued that there was a peak in the growth of continental crust in the late Archean with the result that a high proportion of the present day continents was created at that time. Others have argued that there may have been several peaks in this growth. In any case there do appear to have been peaks in the growth rate of stable crust with a major peak occurring in the late Archean. Many questions can be related to this fundamental growth process, such as: What were the relative contributions of tectonic versus magmatic crustal thickening? What was the role of underplating or overaccretion? When and how did the isostatic uplift and erosion of the thickened crust take place? Some Archean terranes stabilized before others: What implication does this diachronous development have for early continental growth? What were the dynamic P-T paths of the uplifted crust and what do they tell us of the Archean geothermal gradient? Combined research on geochronology and geobarometry should provide information on the rates of uplift of continental crust. The erosion of the late Archean uplifted crust gave rise to clastic sedimentary sequences in early Proterozoic basins and greenstone belts. Study of the detrital minerals in these sequences should provide information on the late Archean crust.

D. Features Associated with Tectonic Problems

It can be useful to consider a variety of crustal features that may help in distinguishing between controversial tectonic models.

(a) Can we distinguish between the andesite versus tonalite models for the upper and lower crust?

(b) Are greenstone belts the remnants of separate tectonized basins or of a once continuous cover?

(c) What were the chemical transfer mechanisms in the formation of granulites in terms of a partial melt or fluid phase?
(d) Were greenstone belts deposited on sialic basement?
(e) What are the implications of the development of sedimentary tectonic basins in the Archean?

(2) The Lunar Crust

The Moon early in its history differentiated a crust which is globally pervasive, was apparently not later recycled, has been intimately reworked by impact and brecciation, and evolved in an anhydrous environment. All four factors distinguish the lunar from terrestrial crustal evolution, at least on a global scale. Local and possibly regional analogies may exist on Earth and it may be that the important lunar petrogenetic processes occurred on Earth, but were most often overshadowed by competing events.

Seismic data show that the lunar crust is about 55-km thick in southern Oceanus Procellarum and varies to as much as 80 km in thickness beneath the highlands. The mare basalts form a thin veneer over the lunar nearside and nowhere exceed several kilometers in thickness. The relationship of gravity to topography on the Moon suggests any of three possibilities: 1) There are isostatic roots under the highlands; 2) Topographic irregularities are supported by lateral petrological variations in the crust; or (3) The crust is chemically stratified. These alternatives are clearly tied to crustal genesis. Basaltic volcanism as a crustal process was active at least as early as 4 billion years ago. A particularly distinctive composition is found in the ancient KREEP (high potassium, rare earths, and phosphorus) basalts, and the genesis of this rock type remains a controversial subject.

Almost all lunar highland samples are breccias displaying multiple lithologies and it is difficult to identify original crustal material. The small number of identified pristine crustal rocks fall into two apparently unrelated groups: magnesian troctolites, dunites, and norites in one group and ferroan anorthosites in the second group.

The major differentiation of the Moon appears to have taken place in the interval 4.4 to 4.5 billion years ago. A major thermal event in the differentiated crust took place about 4.2 billion years ago.

A number of lines of evidence led to a consensus among lunar scientists that the lunar crust was differentiated from a global magma ocean several hundred kilometers thick. Recent petrologic and geochemical evidence, as well as theories of accretional heating, have cast serious doubt on the global ocean hypothesis.

The issues regarding the lunar crust may be cast into the following key questions:

(a) Are there any truly old ($>$4.4 billion years) rocks in the lunar sample collection? If so, are these rocks derived from the primordial differentiation event?

(b) What is the correct interpretation of radiometric ages of 4.2 billion years? Does this relate to a major basin forming event, representing the date of excavation of anorthositic material from a depth in which the $^{40}Ar/^{39}Ar$ clock had not started? Do the 4.2 billion year ages relate only to the Mg-rich rocks and not the ferroan anorthosites?

(c) Are ferroan anorthosites related to the rocks of the Mg-rich soil? Although it does not appear possible by simple petrogenetic processes to generate some of the major and minor element patterns from a single magma, are there more complex and testable processes that will generate the observed petrogenetic dichotomy?

(d) Which samples, if any, crystallized from the magma ocean? Is it two suites, only one suite, or neither?

(e) Was the magma ocean global in scale? The concentration of Al, Ca, Eu, as well as the heat generating elements K, U, and Th into the lunar crust, when taken into consideration with estimates of crustal thickness, imply that at least 50% of the lunar volume must have been differentiated. Does this

large-scale differentiation require a magma ocean? What would be the energy source for the magma ocean and for the differentiation in general? As discussed above, can the two distinct pristine rock sites be derived from a single magma ocean?

(f) Is the KREEP component of local or global origin? In particular, is KREEP basalt a residual from the magma ocean episode with local variations in composition and time of formation?

In summary, one of the enigmatic problems of lunar petrogenesis concerns the relationship between the various "pristine" rocks from the lunar highlands collection, most of which appear to be magmatic cumulates that have been altered to varying degrees by postcrystallization shock, cataclasis and reheating. One supposes that if the effects of mechanical shock and thermal metamorphism were removed, the relationship among a coeval sequence of magmatic cumulates would be obvious—all the more so in the simple framework of the crystallization of a magma ocean. And yet research on the relationship between various pristine lunar rocks has failed to produce a consensus on such fundamental questions as: Was there only one ocean? Or was it a series of lakes? Or perhaps just a pile of lava flows combined with some plutonism? And given any one of the possibilities, what would the relationship between specific samples be? Clearly, the interrelationship of the pristine highlands samples is not obvious at the present time. However, one point which appears to be emerging is that a single, simple magma-ocean model will not accommodate all the presently available data. This implies either that a simple magma-ocean model is inappropriate, or that our understanding of the petrologic consequences of a simple magma-ocean model is faulty—or both.

Most magma-ocean models suggested as guides to the expected constitution of pristine lunar samples are simple applications of a limited number of relatively well understood processes. However, these models are not capable of predicting the details, or even some of the first order features, of the constitution of samples taken from the closest analogs of magma oceans or lakes—terrestrial stratiform layered intrusions.

Petrologic, chemical and isotopic studies of lunar rocks indicate a secular trend in rock types and chemistry from early anorthosites and gabbroic rocks through intermediate-aged KREEP basalts to younger mare basalts. These trends and the observed structural features seem to be explained by the combination of heating effects from accretionary energy, large impacts, and partial melting of mantle material with essentially no effects from internally generated tectonic forces. Most of the crustal chemistry and structure results from very early processes and predates the crustal characteristics observed on Earth. Thus a framework exists for the development of concepts that apply to evolution of the earliest unpreserved crust of Earth.

(3) Other Planetary Bodies

For Mercury there is very little data but the surface features and the implications of spectral data for surface composition are very similar to those of the Moon except for a few but significant thrust faults that suggest a small amount of internally generated tectonic forces.

For Venus the three Venera analyses of K and U in surface materials suggest derivation from both "granitic" and basaltic areas. There are high plateaus or uplands with mountains and low areas of little relief. Whether there are any relations between composition and tectonics within these terrane types is not yet known. The high surface temperature (nearly 500° C) suggests high temperatures in the lithosphere and places constraints on the phase assemblages and tectonic patterns that can exist at or near the surface and within the crust.

Images of Mars show several terranes with different structural features and different ages (from impact crater counts) but it is not clear by what tectonic processes these terranes developed nor what chemical variations may exist between and within terranes. Was plate tectonics ever active? What is the cause of such huge volcanic features? Gravity data indicate an uncompensated load for the volcano Olympus Mons on the Tharsis Plateau, with little associated deformation. This feature probably requires a very thick lithosphere.

The chemical analyses of surface materials at the two Viking lander sites are very similar but difficult to interpret because of the uncertainty about surface alteration processes and surface transport processes.

Some materials, especially the achondrites and perhaps some mesosiderites, may represent crustal materials from other planetary bodies. It has been suggested that some may be derived from Mars although most are thought to represent material from asteroids. Some that are similar to lunar surface breccias may represent surface materials while others may represent samples from various depths in once larger bodies that have been broken up during collision. Further interaction of petrologic, chemical, and isotopic studies may help characterize potential crustal materials from these bodies.

Summary

In order to provide the basic sets of data that are necessary to develop and test hypotheses we must utilize the existing knowledge to:

(a) Select several appropriate field areas on Earth for further detailed multi-disciplinary study including field work, petrology, geochemistry, isotopic work including chronology, and geophysics.

(b) Search for new and clever uses of existing data from other planetary bodies while integrating new data from meteorites into these studies.

(c) Compare crustal features from various planetary bodies to emphasize the similarities and differences in their characteristics and sequences of development.

VII Tectonics

Introduction

Tectonics is defined here as those processes leading to large-scale evolution of planetary lithospheres. Tectonics is intimately tied to planetary thermal evolution in that in all cases it can be characterized as the lithospheric response to the expelling of internal heat. In that sense, the study of present and past tectonic events provides clues to thermal evolution and, conversely, models of thermal evolution may be used to predict tectonic style.

The style of tectonic deformation is fundamentally different on each terrestrial planet. On the Moon and Mercury, much of the active tectonics appears to have taken place before the completion of the period of heavy bombardment and thus has been largely obliterated. That is to say, both of these planets reached their thermal peak well before 3.8 b.y. ago. Tectonic deformation is relatively minor as appropriate for the dwindling phase of thermal evolution; Mercury displays thrust faults perhaps related to volume contraction of the planet. The Moon displays deformation associated with volcanic mass loading of the near-side circular impact basins and modulated by the global lithospheric stress state.

Mars displays active tectonics that occurred after the end of the period of intense bombardment. No evidence for plate tectonics is seen, and the style is perhaps most analogous to continental tectonism on Earth. The Tharsis province is one of the most remarkable tectonic features of the solar system. It is an elevated region occupying some 90° of longitude and reaching heights of 10 km above the surrounding region. It is associated with massive shield volcanoes, extensive fracturing and graben formation, and the largest known gravity anomaly.

Venus is approximately the same size and mass as Earth and if simple axioms relating thermal evolution to planetary size are correct, then one might expect a similar state of neotectonics. The present data sets for Venus suggest, however, that there are large regions of the Venus crust that have been stable over at least the last one billion years. Tectonic activity appears to be confined to relatively small regions of the planet in terms of topography, lineaments, and gravity anomalies. However, this hypothesis depends critically on a crater interpretation of circular features that are pervasively distributed on the plains of Venus.

On Earth, the fundamental question is the extent to which the present style of tectonics (i.e., large-scale lithospheric creation and subduction) can be extrapolated backwards in time. There are many indications that tectonic processes have changed through time, notably the different scales and styles of tectonic and orogenic units in Phanerozoic, Proterozoic and Archean times, and the absence of pre-Archean rocks.

Problems

The most general aspect of the tectonic question concerns the description of a model to predict the tectonic outcome, given the thermal evolution of a planet. Contruction of such a model depends on: (1) understanding the tectonic regime on the Earth from Archean through Phanerozoic, (2) contrasting this with the tectonic style of Venus, which presumably has roughly the same thermal potential as the Earth, and (3) contrasting these large terrestrial planets with the smaller ones, which presumably now display the style of tectonics seen of planets in the last stages of their thermal evolution.

(1) Earth

It is not clear to what extent the changes in tectonic style were due to modifications from the present plate tectonic regime versus the existence of different tectonic regimes (such as a thin, non-subducting lithosphere in which vertical movements were more important than at present). The changes, whether minor or major, were presumably strongly controlled by the contemporary thermal regime, and possibly by the extent of differentiation, distribution, and thickness of continental and oceanic crust.

Major issues involved in these larger questions regarding Earth tectonics are the relationships between Archean granite-granulite terranes and greenstone-gneiss terranes, the relative importance of horizontal versus vertical tectonic movements, the variation of crustal thickness with time, and the mechanisms and timing of cratonization. For example, some current hypotheses relate the greenstone-gneiss terranes to island arcs and back arc basins on the one hand, and to subsiding basins and complementary uplift on the other. Much detailed field and laboratory work may be necessary to decide between these hypotheses.

There is a need for well-posed, quantitative modeling to explore the relationship between the thermal regime and tectonic processes. For example, higher global heat flux may result in faster plate motion, thinner plates, smaller plates, thicker oceanic crust (through higher degrees of partial melting of the mantle), or buoyant oceanic lithosphere (through thicker oceanic crust). In addition, continental crustal thickness will be limited by the geothermal gradient which may or may not be related to the global heat flux. Observations relevant to the history of continental crustal thickness, such as geobarometry, would be valuable for evaluating the roles of processes such as underplating and horizontal compression in determining crustal thickness.

The mechanism behind the growth and stabilization of cratons is largely unknown, and more detailed documentation of this process for several continents would be important. The relationship of cratonization to crustal thickness and the possible role of mantle roots needs to be considered.

A division presently exists between those who have recognized strong evidence of compressional tectonics in Archean rocks and those who consider that Archean rocks are relatively undeformed. Detailed modern structural studies have been reported from few Archean terranes and considerable progress can be expected, particularly in areas where the pace of petrological and geochemical study has outrun that of basic primary field work.

It is common to read statements comparing or contrasting Archean environments with Phanerozoic environments such as rift-systems, marginal basins and arcs. Some of these statements appear relatively poorly-informed about the characteristics of either the modern or the ancient environments and there is a need for improving the dialogue between workers in modern and ancient environments.

Detailed structural studies and the acquainting of workers with environments with which they may be unfamiliar will facilitate testing two basic hypotheses about Archean terranes: 1) that greenstone belt-gneiss terranes are arc-systems driven together by closing oceans and 2) that granulite-granite terranes represent continental crust thickened (mainly by continental collision) and fractionated by partial melting.

(2) Venus

The major problem is establishing the conditions required for lithospheric subduction, and the type of tectonics most likely associated with a planet as thermally active as the Earth but possibly with a non-subducting lithosphere. Of paramount interest is whether or not Venus at any time in its evolution had conditions favorable for Earth-style plate tectonics. Much of the contrast between tectonic styles on Venus and Earth may be related to initial volatile inventory and the volatile degassing history. A first order question for Venus is the present mechanism of support of the topographic features. The answer would shed light on thermal state hypotheses regarding crustal evolution. Major tectonic research required for Venus is development of a thermal history-tectonic model that will account for the presently observed surface features, gravity anomalies, and other known properties. Major variables in the model include the timing of outgassing, the fate of interior volatiles, the time of greenhouse development, and the age of the plains. Of particular interest is the level of equivalence of present-day venusian tectonics with terrestrial Archean tectonics.

(3) Mars

Controversy exists as to whether the elevated Tharsis region is a structural dome or dominantly a vast pile of volcanics loading the lithosphere. Further issues involve whether or not Tharsis represents a "frozen" style of incipient or nascent plate tectonics that on Earth would have developed into full-scale lithospheric recycling. Additionally, there is a basic topographic and physiographic division of Mars with the southern hemisphere geologically old and high-standing and the northern hemisphere young and low-standing. Is this division a primordial crustal feature, analogous to terrestrial continents and ocean basins, or was the ancient surface once globally pervasive (as *is* the lunar crust), with subsequent tectonic destruction of northern hemisphere crust? One also asks whether there is a connection between the global dichotomy and the development of Tharsis. A thermal/tectonic model is needed for the evolution of the martian crust addressing both the north-south dichotomy and the Tharsis issues. Of particular interest is whether Tharsis holds an analogy to certain styles of terrestrial continental crustal features and, if so, what variables would lead to the obvious difference in magnitude of the tectonic effects.

(4) Moon and Mercury

These planets show little evidence of global tectonic style because their crust had undergone nearly complete evolution before the end of the obliterating period of intense bombardment. Nevertheless, it is felt that these planets never had significant endogenically generated lateral variation in tectonic style, in distinct contrast to Mars, Venus, and Earth. The global style of tectonics may best be characterized as "uniform compressional," of which there appears to be good evidence on Mercury (thrust faults) and emerging evidence on the Moon (anticlinal-synclinal folds). For the Moon, a quantitative estimate of the amount of global contraction is lacking, and if derivable, would have important bearing on questions of crustal evolution.

In all, the trend of crustal evolution on the Moon and Mercury, to Mars, and to Venus and Earth appears to represent an increasing level of complexity, and this is apparently manifested in the tectonic styles. Consideration of these contrasts in lithospheric deformation should provide significant insight into crustal evolution.

VIII Paleobiology

Introduction

Microbes may never have ruled the Earth, but they oxidized it. The early evolution of the biosphere and the crust are inextricably linked and equally poorly explored. The ignorance may not be surprising; the present carbon cycle is poorly understood in spite of its crucial involvement in the production and consumption of oxygen, the origin of fossil fuels, and the process of carbonate sedimentation. Reconstruction of the development and stabilization of those interactions is an indispensable part of understanding earliest geologic history.

Archean and Proterozoic paleobiology must also be eventually understood in terms of a fossil record. That record is relatively unorthodox and may never furnish a correlative tool comparable to its Phanerozoic analog, but the linkage between environment and ecology must have been as potent then as now, and the aspects of a succession may eventually emerge.

The Precambrian era covers the first 4 billion years of Earth history during which time Earth's outer layers developed their structure of atmosphere, ocean, crust, and upper mantle; continents differentiated from ocean basins; life originated and evolved most of the energy-yielding metabolic processes now known; the eukaryotic cell originated from prokaryotic ancestors; and the first multi-celled organisms arose.

The Fossil Record

The boundary between the Archean and Proterozoic eras, 2.5 billion years ago, is to some extent arbitrary. It appears to reflect a period of relatively rapid formation and stabilization of continental land masses. The biological impact of this transition in Earth's tectonic style remains a matter for conjecture, but its impact on the fossil record is clear: well-preserved sedimentary rock sequences in which traces of life might be found are rare in the Archean and relatively abundant in the Proterozoic. Thus, many diverse and abundant fossil microbiota of Proterozoic age are known, and these enable the first appearance of Eukaryota to be dated, at least tentatively, at 1.4 billion years ago. By way of contrast, only one indisputable microfossil assemblage of undoubted Archean age has yet been discovered—the 3.5 billion year old North Pole biota in Western Australia.

Because Precambrian organisms lacked the preservable skeletal material that has furnished a rich fossil record for the subsequent Phanerozoic epoch, the course of these crucial early events in the history of the Earth and the history of life on Earth is known only obscurely. Relics of soft-bodied Metazoa are known from the latest Precambrian, about 700 million years ago, but all older evidence of life refers only to microbial forms whose metabolic capabilities and ecological roles cannot be established from appearance alone.

There is other direct evidence of ancient life, however, in the form of stromatolites. Stromatolites are macroscopic mineral structures that preserve the form of dense colonies of microbes that once lived on the interface between sediment and either water or air. They may be thought of as fossilized algal mats of uncertain metabolic capability. About a dozen occurrences of Archean stromatolites are known, the oldest in the 3.5 billion year old North Pole formation. Proterozoic stromatolites are abundant.

The Geochemical Record

The geochemical record represents an especially important adjunct to the fossil record in the Precambrian era. Microbiologists are fond of pointing out that the anatomical diversity of higher organisms is equalled or exceeded by the biochemical diversity of micro-organisms. This statement strikes an almost

eerie resonance in the mind of anyone who juxtaposes the relatively featureless microfossils with their apparent chemical effects on the environment.

It seems clear that the origin and early evolution of life on Earth was profoundly influenced by the chemical and physical conditions of the primitive environment. The earliest microbes evolved metabolic capabilities designed to exploit environmental resources of material and free energy. Evolving life, in turn, affected the environment. As noted, the most striking example of this coevolution of life and its environment is the rise of atmospheric oxygen. A variety of geological, biological, and theoretical lines of evidence indicate that the early Earth lacked significant amounts of free oxygen in atmosphere and ocean. Early photosynthetic organisms, responding perhaps to a shortage of reduced electron donors in their environment, evolved the capability to reduce carbon dioxide to cell material using water as the course of electrons and releasing oxygen as a metabolic waste product. In time, this oxygen accumulated to a level that made possible a new source of metabolic energy, aerobic respiration, that is essential to all of the diverse and abundant multi-celled animals that now inhabit the Earth.

The date of this most important transition in the chemical state of the biosphere is uncertain, but most geological evidence suggests a date of about 2.2 billion years ago. On theoretical grounds, however, it can be argued that oxygen-evolving photosynthesis and aerobic respiration were among the last of the major metabolic developments with the power to change the composition of the environment, having been preceded by fermentation, bacterial photosynthesis, methanogenesis, nitrogen fixation, sulfate reduction, and possibly denitrification. There is, therefore, every reason to suppose that many of the most significant events in the evolution of Earth's biosphere (biota and environment) occurred in the earliest stages of Earth history, the Archean and the early Proterozoic.

Because of the tenuous nature of much of the evidence, the exploration of this all-important early history of the biosphere calls for an interdisciplinary effort involving the insights and expertise of geology, paleontology, geochemistry, microbiology, biochemistry, and geophysics.

Problems

While not inclusive, the following four subject areas represent crucial problems in paleobiology:

(1) What is the Geochemical Record of Early Biospheric Evolution?

The stable isotope records of carbon, sulfur, and oxygen, and the composition of Archean kerogens must all be better defined, in particular their relationships to inorganic geochemistry. It will be particularly interesting to attempt definition of the earliest traces of the geochemical impact of life.

(2) What is the Mode of Formation and Historical Significance of Iron Formations?

These peculiar sedimentary rocks are most abundant in the late Archean and early Proterozoic and are rare or absent in the later geological record. They may well be more indicative of the oxidation state of the atmosphere and hydrosphere than any other comparably abundant rock type. What is the role, if any, of primitive life in the genesis of iron formations? What is the biologic and geochemical relationship to non-iron formation material of equal age?

(3) What is the Evolution of Anaerobic Bioenergetic Pathways?

What is the evolution of sulfur metabolism? What was the most abundant sulfur species in the primitive ocean? Did photosynthetic sulfide oxidation precede or follow sulfate reduction as a source of metabolic energy?

(4) What are the Physiological Controls on the Microbiology of Stromatolites?

Since stromatolites are the most abundant and widespread remains of Precambrian life, what are the conditions that favor their formation and the processes that determine their diverse microbiologies? In particular, what are the physical, chemical, and biological properties of the environments in which stromatolites formed?

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Appendix B

Early Crustal Genesis Steering Committee

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